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A DECISION-SUPPORT SYSTEM APPROACH FOR PAVEMENT MANAGEMENT PLANNING

by

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ABSTRACT

Over the recent years, most agencies responsible for the management of large highway and road networks have been putting an increasing emphasis on pavement management issues. With highway networks which are ageing and deteriorating rapidly, these agencies are forced to undertake a rigorous planning exercise, if the scarce resources which are available for pavement maintenance and rehabilitation are to be allocated in an efficient fashion.

To improve their planning mechanisms, many agencies have resorted to pavement management systems built around optimization models of one type or another. The general tendency in these systems has been to provide planners with a single well-defined optimization model, i.e., with a model in which the objective function and the constraints have been stated once and for all. When the complexity of the issues and of the trade-offs involved in pavement management is considered, one is forced to conclude that this single model approach falls short of fulfilling the needs of decision makers: there are always important questions that remain unanswered. To remedy this situation, we propose a different approach: provide planners with a flexible decision- support tool which lets them specify themselves the optimization problems which seem meaningful within the scope of the decision- making process at any given time.

The core of the proposed decision-support system is a general Markov Decision Process structure in which administrative divisions of the highway network (regions, districts) are explicitly taken into account. This basic structure is stated in an equivalent linear programming format which then allows for the addition to the model of various linear constraints.

The other fundamental element of the system is a formal descriptive framework which is made up of two languages:

- a **network language** which is used to describe the condition states, the administrative structure, the highway categories, the transition matrices describing pavement evolution through time, the maintenance and rehabilitation actions, and various linear functions defined over the set of condition states or actions (performance ratings, costs, etc.);
- a **scenario language** which allows a planner, who is unfamiliar with optimization models and techniques, to define the optimization problem that he or she wants to have solved with only a few statements.

In this paper, we provide a description of both languages, of the general Markov Decision Process structure, and of the current computer implementation of the system. Planned future developments are also outlined.

Key words: pavement management; planning; decision-support; optimization.

RÉSUMÉ

Nous présentons un système d'aide à la décision pour la planification à moyen et long terme des interventions d'entretien et de réhabilitation des chaussées sur un réseau routier de grande taille.

Le modèle mathématique sur lequel repose ce système est un modèle de décision markovien avec contraintes supplémentaires, semblable aux modèles utilisés dans les systèmes de gestion des chaussées de plusieurs états américains; notre modèle diffère cependant de ces modèles par le fait qu'il permet de tenir compte explicitement de la structure administrative (découpage en régions et districts) du réseau étudié.

L'autre élément distinctif du système proposé est un cadre descriptif formel constitué de deux langages :

1) **Un langage de description de réseaux** que le planificateur doit utiliser pour spécifier les paramètres du réseau étudié : la structure administrative (régions, districts), les catégories de routes (autoroutes, routes principales, secondaires, etc.), les états possibles des diverses chaussées, les interventions permises en fonction des états, les fonctions caractérisant les états et les interventions (indicateurs de performance, coûts, etc.), la matrice de transition décrivant l'évolution des chaussées dans le temps, l'état initial du réseau.

2) **Un langage de description de scénarios** permettant à un usager non familier avec la programmation mathématique de spécifier en quelques énoncés le problème particulier qui l'intéresse en termes de réseau à considérer, d'horizon de planification, d'objectif à optimiser, de contraintes à respecter et d'état-cible à atteindre à la fin de l'horizon.

Dans cet article, nous présentons ces deux langages, le modèle de décision markovien et l'implantation informatique actuelle du système. Nous indiquons aussi les développements futurs prévus.

Mots-clés : entretien routier; réhabilitation des chaussées; planification; modèle mathématique; optimisation; système d'aide à la décision.

1. INTRODUCTION

Over the recent years, most agencies responsible for the management of large highway and road networks have been putting an increasing emphasis on pavement management issues. With highway networks which are ageing and deteriorating rapidly, these agencies are forced to undertake a rigorous planning exercise, if the scarce resources which are available for pavement maintenance and rehabilitation are to be allocated in an efficient fashion.

To improve their planning mechanisms, many agencies have resorted to pavement management systems (PMSs) built around optimization models of one type or another. A non-exhaustive list of these agencies includes the departments of transportation of the states of Arizona (4, 11), Florida (8), and Texas (1) in the United States, the ministries of transportation of the provinces of Ontario (3) and Manitoba (5) in Canada, of Denmark (10) and Finland (9), as well as the World Bank (7).

The general tendency in these systems has been to provide planners with a single well-defined optimization model, i.e., with a model in which the objective function and the constraints have been stated once and for all. When the complexity of the issues and of the trade-offs involved in pavement management is considered, one is forced to conclude that this single model approach falls short of fulfilling the needs of decision makers: there are always important questions that remain unanswered. To remedy this situation, we propose a different approach: provide planners with a flexible decision- support tool which lets them specify themselves the optimization problems which seem meaningful within the scope of the decision-making process at any given time.

It should be noted that, on our part, the decision to adopt this decision-support system (DSS) approach for pavement management planning was arrived at after a series of meetings and discussions with officials of the

Ministry of Transportation of the province of Quebec in Canada. Throughout these discussions, they stressed the multi-objective nature of pavement management and they clearly indicated the need of having a flexible computerized planning tool for addressing their planning problems.

To clearly illustrate how the DSS approach can work for pavement management, we describe in this paper a specific DSS which focusses on **strategic planning** (also called network level planning by some authors) issues in large highway networks, i.e., allocation of budgets to various highway categories and to administrative units (regions, districts), setting of priorities and performance objectives, evaluation of major rehabilitation or maintenance programs, etc. over a medium to long-term planning horizon. This system is intended to be integrated with a **tactical planning** (or programming) system to form a truly comprehensive pavement management system along the lines proposed by Gendreau (2).

The two key "elements" of the proposed DSS are a **basic optimization framework** (a generic optimization model) and a **formal descriptive environment** for pavement management planning problems. The basic optimization framework provides decision-makers with a "skeleton" optimization model which they can "flesh out" by using the formal descriptive environment.

In the remainder of the paper, we first describe the key elements of the DSS, we then provide some examples of problem description within the system and discuss the computer implementation of the system; a short discussion of possible future developments and improvements concludes the paper.

2. THE BASIC OPTIMIZATION FRAMEWORK

When one is faced with the task of choosing an optimization framework around which a DSS will be built, it is of prime importance to properly assess the objectives of the envisioned system. In the case under consideration here the intended use of the system is, as we stated earlier, strategic planning for large highway networks. For such purposes, it seems preferable to choose an aggregate model, (i.e., a model in which pavements are grouped together according to some criterion), rather than a disaggregate one (i.e., a model in which individual highway sections are explicitly identified), since this will ease the computational burden (this may be a critical factor, if the network is very large) and will also help decision makers to focus their attention on critical issues (see (2, 3) for a more detailed discussion on this topic).

Amongst the aggregate optimization formulations for pavement management planning, the most popular are undoubtly those of the **Markov Decision Process (MDP)** type, which were first introduced in the Network Optimization System of the state of Arizona (4, 11). In those models, the grouping criterion for pavements is their **condition state** (a combination of characteristics or attributes relative to their current condition and possibly their dynamic behavior), and pavement evolution over time, which corresponds to transitions between condition states, is described in a probabilistic fashion.

An interesting feature of MDP type models is that they can be reformulated in a linear programming (LP) format. This reformulation is advantageous in many ways: (i) the model may be easily solved using standard LP packages; (ii) arbitrary linear constraints may be freely added to the LP formulation to account for other aspects of the planning problem (it should be pointed out however that adding such constraints to the model "destroys" its MDP nature from a formal viewpoint).

With these advantages in mind, it was thus decided to choose an MDP with additional linear constraints structure for the optimization framework. The specific MDP model which is the core of the framework differs however from previous models in that administrative divisions of the highway network (regions, districts) are explicitly taken into account in the formulation. The reasons for this are two-fold:

(i) This model will allow for a much easier interfacing between the DSS and the future tactical planning system (see (2) for further details).

(ii) This model provides decision makers with a much richer environment for problem statement, since it makes it possible to define constraints relative to the administrative divisions of the network.

We now proceed to formally describe this MDP model. To do so, we first state a number of assumptions regarding the network under consideration:

(1) The network is divided into a number of basic administrative units (which we shall call "districts" in the following) which may be grouped in larger units (which we call "regions").

(2) The highways and roads of the networks may be classified into a number of "categories" (e.g. highways, primary roads, and secondary roads). Furthermore, within each category, we may distinguish, if desired, several "types" corresponding to different construction techniques or materials, traffic load ranges, environment, etc. It is assumed that the type of a given pavement section will remain the same throughout the planning horizon and that for any given type the sections of this type are reasonably homogeneous with regard to their dynamic behavior.

(3) For every type, it is possible to define a set of condition states which accurately depict serviceability and dynamic behavior.

(4) For every state of every type, the set of possible maintenance and rehabilitation alternatives is well-defined and non-empty, i.e., there is always one action (which may be a "do nothing" or "routine maintenance" action) which may be performed.

(5) The planning horizon (which may be infinite) is fixed and is divided into a number of equal-length periods (usually one year).

(6) For every type ℓ, every pair (s', s) of states of type ℓ, every action a which is allowed in state s', the probability that a pavement section in state s' will be in state s at the beginning of the next period $p^{\ell a}_{s's}$ is known, stationary (independent of time), and independent of location (district).

To simplify the exposition, let us introduce the following notation:

D, the set of districts;

R, the set of regions;

D_r, the set of districts in region r, $r \in R$;

C, the set of categories;

L, the set of types;

L_c, the set of types for category c, $c \in C$;

S_ℓ, the set of states for type ℓ, $\ell \in L$;

A, the set of M&R actions;

$A_{\ell s}$, the set of allowable actions for state s of type ℓ, $\ell \in L$, $s \in S_\ell$;

T, the planning horizon limit (if finite);

$b^d_{\ell s}$, the number of lane-miles of type ℓ in state s in district d at the beginning of the planning horizon, $d \in D$, $\ell \in L$, $s \in S_\ell$.

We may now state the model in the finite and the infinite planning horizon cases.

2.1 Finite horizon model

In this model, we wish to trace the evolution from period to period starting from the beginning of period 1 to the end of period T. The decision variables are then of the form $x_{\ell s}^{adt}$ with $\ell \in L$, $s \in S_\ell$, $a \in A_{\ell s}$, $d \in D$, $t \in \{1, \ldots, T\}$ and they correspond to "the expected number of lane-miles in state s of type ℓ in district d upon which action a will be performed during period t". These variables are linked from one period to the next by a set of **dynamic constraints** which impose a consistent description of the evolution of the network. To better understand these constraints, let us introduce first a set of dummy variables $y_{\ell s}^{dt}$ which correspond to "the expected number of lane-miles in state s of type ℓ in district d at the beginning of period t".

First note that since an action must be performed on every pavement section in every period, one must have

$$\sum_{a \in A_{\ell s}} x_{\ell s}^{adt} = y_{\ell s}^{dt}, \qquad \forall \ell \in L, \ \forall s \in S_\ell, \ \forall d \in D, \ \forall t \in \{1, \ldots, T\}. \tag{1}$$

Now, by using the transition probabilities, we may see that

$$\sum_{s' \in S_\ell} \sum_{a \in A_{\ell s'}} p_{s's}^{\ell a} \, x_{\ell s'}^{adt} = y_{\ell s}^{d(t+1)}, \ \forall \ell \in L, \forall s \in S_\ell, \forall d \in D, \forall t \in \{1, \ldots, T\},$$

or equivalently

$$\sum_{s' \in S_\ell} \sum_{a \in A_{\ell s'}} p_{s's}^{\ell a} \, x_{\ell s'}^{ad(t-1)} = y_{\ell s}^{dt}, \ \forall \ell \in L, \forall s \in S_\ell, \forall d \in D, \forall t \in \{2, \ldots, T\}. \tag{2}$$

Subtracting (2) from (1), we get the final form of the constraints:

$$\sum_{a \in A_{\ell s}} x_{\ell s}^{adt} - \sum_{s' \in S_\ell} \sum_{a \in A_{\ell s'}} p_{s's}^{\ell a} \, x_{\ell s'}^{ad(t-1)} = 0, \ \forall \ell \in L, \forall s \in S_\ell, \forall d \in D, \forall t \in \{2, \ldots, T\}. \tag{3}$$

For t=1, we have $y^{d1}_{\ell s} = b^{d}_{\ell s}$ and we obtain the following constraint:

$$\sum_{a \in A_{\ell s'}} x^{ad1}_{\ell s'} = b^{d}_{\ell s}, \qquad \forall\, \ell \in L,\ \forall s \in S_\ell,\ \forall d \in D. \qquad (4)$$

Given any linear objective function defined by coefficients $f^{adt}_{\ell s}$ for all values of a, d, t, ℓ and s, the finite horizon model consists of optimizing (i.e., minimizing or maximizing) the objective function

$$Z = \sum_{t=1}^{T} \sum_{d \in D} \sum_{\ell \in L} \sum_{s \in S_\ell} \sum_{a \in A_{\ell s}} f^{adt}_{\ell s}\ x^{adt}_{\ell s}$$

subject to the dynamic constraints (3) and (4) and to non-negativity constraints on the $x^{adt}_{\ell s}$.

2.2 Infinite horizon model

In this model, we are interested by the long-term behavior of the network under a systematic repetitive policy. We may thus drop the "t" subscript from the decision variables which are now $x^{ad}_{\ell s}$. Without a period index, the dynamic constraints "wrap around" on themselves to take the form

$$\sum_{a \in A_{\ell s}} x^{ad}_{\ell s} - \sum_{s' \in S_\ell} \sum_{a \in A_{\ell s'}} p^{\ell a}_{s's}\ x^{ad}_{\ell s'} = 0, \qquad \forall\, \ell \in L,\ \forall s \in S_\ell,\ \forall d \in D. \qquad (5)$$

To account for the number of lane-miles of each type in each district, we must add a new set of constraints:

$$\sum_{s \in S_\ell} \sum_{a \in A_{\ell s}} x^{ad}_{\ell s'} = \sum_{s \in S_\ell} b^{d}_{\ell s}, \qquad \forall\, \ell \in L,\ \forall s \in S_\ell,\ \forall d \in D. \qquad (6)$$

It should be pointed out that some constraints in the set (5) are redundant and that they should be dropped. It is also possible that the model may breakdown if the types and states are not properly defined. Such occurrence is not possible in the finite horizon model.

3. THE FORMAL DESCRIPTIVE ENVIRONMENT

The objective of the formal descriptive environment is to permit a user who is unfamiliar with mathematical programming techniques to fully describe planning problems within the optimization framework previously defined.

It is interesting to note that the problem description may be broken down into two parts: the first part consists of a description of the highway and road network under consideration, i.e., of its logical (categories, types, states, actions) and administrative structure, as well as of all the relevant parameters (transition matrices, initial state, costs, commonly used performance measures, etc.); the second part is concerned with scenario objectives, etc.). To formalize this conceptual division, we have developed a descriptive environment which is made up of two languages: a network description language and a scenario specification language. It should be stressed that the level of technical sophistication required to set up network descriptions is much higher than that for scenario specification. It would thus be possible within an agency to have one person who is more technically knowledgeable being in charge of setting up and maintaining various network description files while the rest of the staff would only have to learn and understand scenario specification to take advantage of the DSS.

We now briefly describe the two languages.

3.1 The network description language

The network description language is a formal language for setting up network description files within the DSS. It specifies the exact format and sequence of elements within such a file. The structure of such a file is as follows:

- network identification block: network name, date, length of description horizon;

- geographic block: number of regions and districts, listing of districts within regions;
- category structure: listing of names of categories;
- type and state structure: for each category, listings of all types with associated condition states;
- action structure: listing of all possible actions with their names and the subset of condition states for which they are allowed;
- function structure: a list of linear functions stating for each one its name, whether it applies to the action variables (the **x** variables of the previous section) or to the dummy state variables (the **y** variables) and all of its coefficients;
- initial state structure: a listing of the **b** parameters of the previous section;
- transition matrix structure: a listing of the **p** parameters of the model.

As can be deduced from this enumeration, setting up a network description file is a substantial task. To somewhat alleviate this burden, we have tried using compact notations (e.g. for specifying groups of coefficients at one time) whenever possible.

3.2 The scenario specification language

The scenario specification language is a formal language for setting up scenario specification files within the DSS. The general structure of those files is fairly simple since it consists of one line for defining the length of the planning horizon for the scenario, one line for stating the objective function of the model, a few lines for specifying the linear constraints to be added to the basic model, and eventually a "target" specification for the network at the end of the planning horizon.

Within the scope of this language, all functions that are used are always referred to by their mnemonic names (which have been defined in the network description file).

The key feature of this language is the syntax of the CONSTRAINT statement which allows for the specification of whole families of similar constraints by single occurrences of the statement, and for complex patterns in the definition of index scope within those families.

To illustrate this, we now present a few examples.

4. EXAMPLES

Let us consider a highway and road network divided into 10 districts (numbered from 1 to 10) grouped in 3 regions (numbered from 1 to 3) with 3 categories of highways and roads (highways, primary roads, and secondary roads) and 4 possible actions (patching, resurfacing, do-nothing, and crack sealing – CRACKSEAL). For each category there is a single type and 6, 5, and 4 condition states respectively have been defined for highways, primary roads, and secondary roads. Let us also assume that 4 functions have been defined for that network in the network description file:

- COST which gives for each action the average cost per lane-mile taking into account category and condition state;
- UNACCEPT which is a 0-1 function stating whether a given condition state is considered unacceptable for the category in question;
- PCI which gives on a 0-100 scale the average pavement condition index for each state;
- MILEAGE which is a dummy function taking the value 1 for every action and state.

To minimize the total cost of the maintenance and rehabilitation program for that network over a four-period planning horizon, a very short scenario specification file would suffice:

(1.1) NETWORK EXAMPLE

(1.2) HORIZON 4

(1.3) OBJECTIVE MINIMIZE COST.

To solve this simple scenario, 600 dynamic constraints must be generated by the system (one constraint for each period-district-state combination: 4 x 10 x (6+5+4)).

One could also specify scenarios which include very complex constraint sets. Consider the following, for example:

(2.1) NETWORK EXAMPLE

(2.2) HORIZON 4

(2.3) OBJECTIVE MINIMIZE UNACCEPT

(2.4) CONSTRAINT COST < 500,000

(2.5) CONSTRAINT COST PERIOD * < 150,000

(2.6) CONSTRAINT COST DISTRICT * > 20,000

(2.7) CONSTRAINT MEAN PCI HIGHWAYS PERIOD * > 75

(2.8) CONSTRAINT MILEAGE CRACKSEAL PERIOD 1,2 < 500

(2.9) CONSTRAINT MEAN UNACCEPT CATEGORY * REGION * PERIOD * < 0.1.

Since we have the same network and horizon as before, there will be 600 dynamic constraints, but we will have many other constraints:

- statement (2.4) generates a global budget constraint of $500,000 for the whole M&R program;
- period budget constraints of $150,000 are enforced by statement (2.5) (4 constraints over all);

- statement (2.6) imposes a lower bound of $20,000 on total expenses for each of the 10 districts (10 constraints);

- in statement (2.7), we ask that the mean PCI (computed over the whole network) of highways be at least 75 during each of the periods (4 constraints);

- statement (2.8) corresponds to a policy of limiting crack sealing to no more than 500 lane-miles in each of the first two periods (2 constraints);

- the proportion of unacceptable highways and roads is upper-bounded to 10% (0.1) for each category-region-period combination by statement (2.9) (36 constraints).

It should also be noted that the objective function has been changed: we are minimizing the total lane-mileage of unacceptable highways and roads over the planning horizon.

5. COMPUTER IMPLEMENTATION

Under the proposed DSS approach, the complete solution process of a strategic planning problem is made up of the following steps:

(1) setting up the network description and scenario specification files;

(2) translating the user-representation of the problem into a mathematical statement in an adequate format;

(3) solving the optimization problem;

(4) reporting results of the optimization routine in a user-friendly format.

Since there exists a large number of linear programming packages available on the market, we decided that we would not develop new software for this purpose, but rather use one of the existing packages: XMP of R.E. Marsten (5).

Up to now, we have developed a program which constructs an XMP input file from both network description and scenario specification files, a validation program for scenario specification files which verifies that those files are set up in accordance with the formal language and which detects and flags erroneous statements, and simple procedure for translating back XMP output into a form which is understandable.

6. FUTURE DEVELOPMENTS

We intend to keep on developing the component programs required for full implementation of the DSS approach that we have proposed.

In the near future, we intend to focus on two major items within the system:

a) set-up of the network description and scenario specification files for which we plan to develop interactive entry programs;

b) development of a powerful system which would include tables, plots, graphics, etc., for presenting the results of the optimization software.

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